

Higher Charmonium

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Abstract. This contribution briefly discusses some new theoretical results for the properties of charmonium, especially the “higher charmonium” states above open-charm threshold. In particular we discuss the spectrum of states, open-flavor strong decays, and the surprisingly large effects of virtual decay loops of charmed meson pairs.

1. Introduction

Recently there have been several experimental reports of hadrons with remarkable and unexpected properties. These include the surprisingly low mass charm-strange mesons $D_{s0}^{*+}(2317)$ [1] and $D_{s1}^{+}(2460)$ [2], the charmonium or charmed meson molecule candidate $X(3872)$ [3], and the pentaquark candidate $\theta(1540)$ [4, 5]. These reports motivate careful, detailed studies of the physics underlying the resonances observed in these sectors, both to determine what properties are expected for accessible states where the calculations are incomplete, and also to determine “what has gone wrong” with the existing models. In this contribution we abstract some predictions for properties of higher mass charmonium states (specifically the spectrum and strong decay widths) from one such detailed study, which is currently in preparation [6]; some closely related results for charmonium were published previously in a study of possible $X(3872)$ assignments [7].

2. Spectrum

It is well known that a simple potential model gives a remarkably good description of the charmonium spectrum. The spectrum predicted by a model of this type, including all multiplets with entries below 4.4 GeV, is given in Table 1. This “minimal” model uses the nonrelativistic Schrödinger equation, with a zeroth-order potential consisting of the color Coulomb plus linear scalar confining terms and a Gaussian-smeared OGE spin-spin hyperfine interaction. The OGE spin-orbit and tensor and scalar confinement spin-orbit terms are incorporated in first-order perturbation theory. The four parameters α_s (OGE strength), b (string tension), m_c (charm quark mass) and $1/\sigma$ (hyperfine smearing length) are determined by a fit to the well-established experimental states given in the table. The results are shown in Fig.1, together with the spectrum predicted by the relativized Godfrey-Isgur model [8]. The spectra are rather similar, although the NR model gives somewhat lower masses for higher-L states, largely due to the choice of a smaller string tension. We note in passing that recent quenched LGT results for the spectrum of charmonium [9] are very similar to the predictions of these potential models.

The generic features of the resulting spectrum, which are well known, are slowly decreasing radial excitation energy gaps with increasing N and L , and rapidly decreasing splittings within a multiplet with increasing L (due to suppressed short-distance wavefunctions). For sufficiently large L the multiplets invert, due to the increased importance of the inverted scalar spin-orbit term. This effect however may be obscured by other mass shifts.

Table 1. Spectrum of charmonium states in a nonrelativistic potential model (masses in MeV). The experimental states used as input are shown in brackets, and the resulting parameters are $\alpha_s = 0.5461$, $b = 0.1425 \text{ GeV}^2$, $m_c = 1.4794 \text{ GeV}$ and $\sigma = 1.0946 \text{ GeV}$. All multiplets with any state below 4400 MeV are shown.

Multiplet	$M_{S=1}^{J=L+1}$	$M_{S=1}^{J=L}$	$M_{S=1}^{J=L-1}$	$M_{S=0}^{J=L}$
input:				
1S	[3097]			[2979]
2S	[3686]			[3638]
3S	[4040]			
4S	[4415]			
1P	[3556]	[3511]	[3415]	
1D			[3770]	
2D			[4159]	
predictions:				
1S	3090			2982
2S	3672			3630
3S	4072			4043
4S	4406			4384
1P	3556	3505	3424	3516
2P	3972	3925	3852	3934
3P	4317	4271	4202	4279
1D	3806	3800	3785	3799
2D	4167	4158	4142	4158
1F	4021	4029	4029	4026
2F	4348	4352	4351	4350
1G	4214	4228	4237	4225
1H	4392	4410	4424	4407

3. Strong Widths

Strong width predictions for higher-mass charmonium states are of great importance, since they indicate which states should be narrow enough to identify easily, and which modes should be favored by a given state. The dominant strong decays (when energetically allowed) are open flavor decays, which in the valence approximation are due to the process $(c\bar{c}) \rightarrow (c\bar{q})(q\bar{c})$. (Here, $q = u, d, s$.) This strong decay mechanism is surprisingly poorly understood in terms of QCD degrees of freedom [10], and is usually (for light hadrons) described using the phenomenological “ 3P_0 model” [11]. This model assumes that the new $q\bar{q}$ pair is produced with vacuum quantum numbers, with a universal dimensionless amplitude γ that is determined by the data. (Light meson decays suggest a value of $\gamma \approx 0.4$ [12].) In charmonium an alternate model, in which the $q\bar{q}$ pair is produced by a linear vector confining interaction, was introduced by the Cornell group [13] and has been employed in recent studies by Eichten *et al* [14].

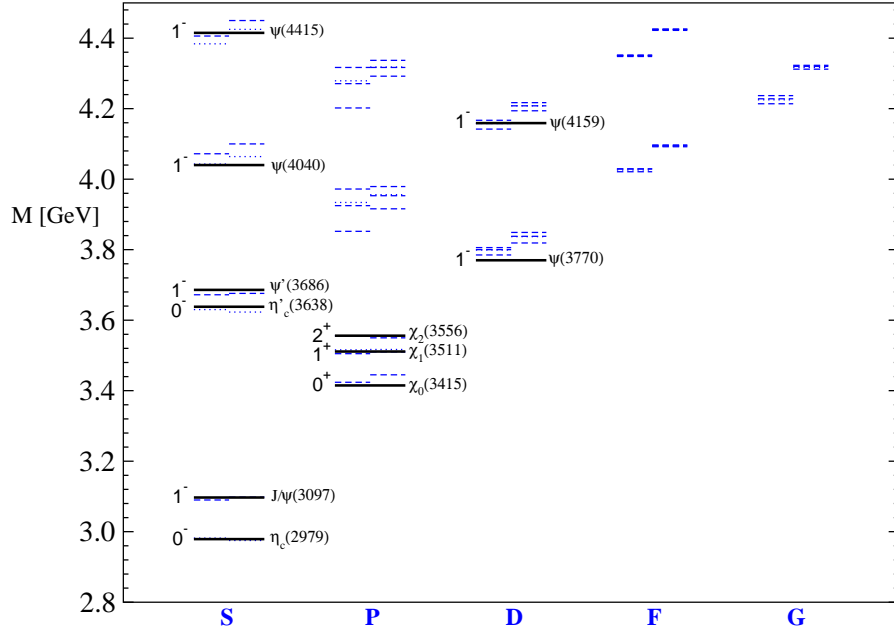


Figure 1. The spectrum of states (to $L=4$) predicted by the nonrelativistic (left) and Godfrey-Isgur (right) potential models. The well-established experimental states used as input for the NR model are also shown (solid).

Application of this model to charmonium gives predictions for all the two-body open charm decay amplitudes and partial widths of every state, which is clearly a great deal of information. In view of the limited space, here we only quote the partial and total widths of the four known states above DD threshold, which are the $\psi(3770)$, $\psi(4040)$, $\psi(4159)$ and $\psi(4415)$. These results are given in Table 2.

Little is known about these strong branching fractions experimentally, which is unfortunate because a striking preference for certain modes is predicted, such as DD_1 being the largest mode of the $\psi(4415)$. The weakness of $\psi(4040) \rightarrow DD$ agrees with experiment [15], but the exclusive branching fractions of the $\psi(4159)$ and $\psi(4415)$ have unfortunately not been measured. These exclusive decays will hopefully be studied at CLEO-c and BES in the near future. We also note that the mode D^*D^* is very interesting, in that it has three 1^{--} waves, 1P_1 , 5P_1 and 5F_1 , and the relative decay amplitudes depend strongly on the nature of the initial $c\bar{c}$ state. For S-wave $c\bar{c}$ mesons (presumably including the $\psi(4040)$ and $\psi(4415)$) the 3P_0 model predicts the amplitude ratio $^5P_1/^1P_1 = -2\sqrt{5}$ and $^5F_1 = 0$, whereas for the D-wave $\psi(4159)$ one finds a dominant 5F_1 amplitude, and $^5P_1/^1P_1 = -1/\sqrt{5}$. A measurement of these amplitude ratios would provide a sensitive test of the decay model (assuming that the usual spectroscopic assignments are correct).

4. Loop Effects

At second order in the decay process one finds contributions to the composition and properties of hadrons due to virtual hadron loops. In charmonium, the process $(c\bar{c}) \rightarrow (c\bar{n})(n\bar{c}) \rightarrow (c\bar{c})$ describes the virtual transition of a “bare” quark model $c\bar{c}$ meson into two open-charm mesons. The associated energy shift has real and imaginary parts, which give respectively the mass shift due to two-meson continuum mixing and the decay rate. (The imaginary part is zero if the state is below threshold.) The first-order correction to the $|c\bar{c}\rangle$ state is of the form $|(c\bar{n})(n\bar{c})\rangle$, which specifies the continuum components of the charmonium resonance.

Table 2. 3P_0 model predictions for the partial and total widths (MeV) of known charmonium states above DD threshold. This assumes SHO wavefunctions with a width parameter $\beta = 0.5$ GeV, a pair production strength $\gamma = 0.4$, and the usual spectroscopic assignments $\psi(3770) = 1^3D_1$, $\psi(4040) = 3^3S_1$, $\psi(4159) = 2^3D_1$ and $\psi(4415) = 4^3S_1$.

State	DD	DD*	D*D*	D _s D _s	D _s D _s *	D _s *D _s *	DD ₁	DD' ₁	DD ₂ *	Γ_{tot} [expt.]
$\psi(3770)$	43.									43. $[23.6 \pm 2.7]$
$\psi(4040)$	0.1	33.	33.	7.8						74. $[52 \pm 10]$
$\psi(4159)$	16.	0.4	35.	8.0	14.					74. $[78 \pm 20]$
$\psi(4415)$	0.4	2.3	16.	1.3	2.6	0.7	31.	1.0	23.	78. $[43 \pm 15]$

The size of these non-valence components and their effects on observables are interesting topics, since they are neglected in the valence approximation to the quark model and in quenched lattice QCD. The possibility that loop effects (mixing with the two-meson continuum) may be responsible for the anomalously low masses of the new D_{sJ} states has been suggested by several groups [16, 17, 18], and was the principal motivation for our study of loop effects.

We have tested the importance of loop effects in charmonium by calculating the mass shifts and state composition for several charmonium states that result from loops of S-wave $c\bar{n}$ and $c\bar{s}$ meson pairs (six channels), using the 3P_0 model with the same parameters used previously to describe decays [19]. The results for all 1S, 1P and 2S $c\bar{c}$ states are shown in Table 3. Evidently

Table 3. The effect of virtual meson loops on charmonium states below DD threshold. The mass shifts (MeV) due to each mixing channel and the residual $|c\bar{c}\rangle$ probability $P_{c\bar{c}}$ are shown.

State	Mass Shift by Channel (MeV)						Total	$P_{c\bar{c}}$
	DD	DD*	D*D*	D _s D _s	D _s D _s *	D _s *D _s *		
$ 1^3S_1(J/\psi)\rangle$	−30.	−108.	−173.	−17.	−60.	−97.	−485.	0.65
$ 1^1S_0(\eta_c)\rangle$	0	−149.	−137.	0	−84.	−78.	−447.	0.71
$ 1^3P_2(\chi_{c2})\rangle$	−53.	−137.	−188.	−22.	−59.	−79.	−537.	0.43
$ 1^3P_1(\chi_{c1})\rangle$	0	−165.	−194.	0	−66.	−85.	−511.	0.46
$ 1^3P_0(\chi_{c0})\rangle$	−75.	0	−255.	−28.	0	−113.	−471.	0.53
$ 1^1P_1(h_c)\rangle$	0	−194.	−169.	0	−81.	−73.	−516.	0.46
$ 2^3S_1(\psi')\rangle$	−36.	−110.	−165.	−11.	−36.	−56.	−413.	0.45
$ 2^1S_0(\eta'_c)\rangle$	0	−154.	−134.	0	−52.	−46.	−386.	0.58

the mass shifts and continuum mixing predicted by the 3P_0 model are indeed quite large, and it is surprising *a priori* that $c\bar{c}$ potential models describe the spectrum as accurately as they do (recall Fig.1). Presumably this is because the large negative mass shift is similar for all the low-lying charmonium states, and can be approximated by a change in the charm quark mass. Note in this regard that the residual scatter of total mass shifts within each multiplet (mean variance 19. MeV) in Table 3 is much smaller than the mean shift (−471. MeV). If the assumed initial “bare” masses of the states within an N,L $c\bar{c}$ multiplet are set equal, as are the masses of the charmed mesons in the loops, we actually find that the total mass shift is the same for every state within the multiplet. In any case, we conclude that loop effects are quite large, and should

certainly be incorporated in future studies of the effects of “unquenching the quark model”.

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